Cosmic-Ray Intensities during the Space Age and the Holocene

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The intensity of cosmic rays that reach in the inner solar system is modulated by the solar wind and its embedded magnetic field.
Cosmic-ray intensity variations are anti-correlated with solar activity

Cosmic-ray modulation is a complex process - it is usually parameterized by changes in the interplanetary diffusion coefficient ($K$) due to variations in the turbulence in the interplanetary magnetic field ($\Delta B/B$).

![Sunspot Number](image)

Neutron monitor count rates at 3 and 13 GV cutoff rigidities

Note the 22-year periodicity
Cosmic-ray spectral variations over the solar cycle

Spectral shape changes are reasonably-well accounted for by the "modulation parameter" ($\phi$):

$$\phi \propto \int_{1 \text{ AU}}^{\text{boundary}} \frac{V_{SW}}{\kappa} \, dr$$

Here $V_{sw}$ is the solar wind speed, and $\kappa$ is the diffusion coefficient, which depends on the magnetic field strength and turbulence level.

from Wiedenbeck (2007)
Outline

Introduction
Cosmic ray access to the heliosphere
Evidence for record-breaking intensities in 2009-2010
Energy spectra
Cosmic Rays in the Atmosphere
What enabled the 2009 intensity increase?
Cosmic rays over the past 80, 600, and 9300 years
Deriving the solar magnetic field and TSI
Voyager in the ISM
Summary

Sources of Data
Cosmic rays: ACE, HEAO, IMP-8, Voyager,
Lebedev Balloon Flights, BESS, PAMELA, Newark and Climax neutron monitors, $^{10}$Be and $^{14}$C data from Beer et al.
Solar Wind: ACE, Ulysses
CMEs: SOHO, STEREO
Based on solar cycles 19-22 the GCR intensity was expected to decline in 2008.

At the time GCR intensities were approaching those in 1997-98 and in 1976.

Instead, solar minimum persisted, and GCRs began to increase in early 2008, reaching record levels in 2009.

In early 2010 the intensities suddenly returned to 1997 levels

Mewaldt et al. 2010
All Abundant Species Have Similar Excesses in 2009-2010

Mewaldt et al. 2010
Cosmic Ray Energy Spectra

The "modulation parameter":

\[ \phi \propto \int_{1 \text{ AU}}^{\text{boundary}} \frac{V_{SW}}{\kappa} \, dr \]

ACE/CRIS Data
Comparing 100-200 MeV/n He over 5 Solar Minima

20% ± 2%

Mewaldt et al. 2010
What About Protons?

ACE has a count rate that responds to >120 MeV protons

We find a >120 MeV excess of $13.7 \pm 2.0\%$ in late 2009
The radiation dose increased by a similar amount
Scaling from the Newark neutron monitor, Climax would be at record levels in 2009!

The figure shows a line graph of Climax neutron monitor 27-day rate from 1952 to 2008. The red line represents Climax, and the blue line represents Climax, scaled from Newark. The graph indicates a significant increase in neutron rate compared to previous years, with up 4.2% from 1977 & 1997-98 and up 2.1% from 1987.
Cosmic Rays in Space and the Atmosphere

Ionization Rate

Stozhkov et al. 2007
Atmospheric Particle Coupling

After Lean (1994)
50 Years of Cosmic-ray Intensities in the Stratosphere

Stratospheric Balloon Data
YI Stozhkov, et al.. LPI Preprint No. 14, 2007

Blue Mumansk  \( P_c = 0.6 \text{ GV} \)
Red Moscow  \( P_c = 2.4 \text{ GV} \)
Black Mirny  \( P_c = 0.03 \text{ GV} \)

Normalized to March 1987 = 100
Solar/Interplanetary parameters affecting cosmic ray intensity:

1) The interplanetary magnetic field is at its lowest level of the space age (Smith & Balough 2008). Solar wind turbulence has also decreased

- The magnetic field strength determines the gyroradius of cosmic rays and the turbulence level affects their scattering rate
- Burlaga & Ness (1998) and Cane et al. (2003) have shown that cosmic-ray intensity is antecorrelated with the IMF strength

![Graphs showing Cosmic Rays and the IMF, Cosmic Rays and δB](ACE/MAG & CRIS data)
2) The Tilt-Angle of the Heliospheric Current Sheet

- The GCR increase in 2008 was triggered in part by a decrease in the tilt of the heliospheric current sheet (HCS)
- There is a good inverse correlation of intensity and tilt-angle

Jokipii and Thomas, 1981

HCS tilt data from Wilcox Solar Observatory

Mewaldt et al. 2010
Solar/Interplanetary Parameters affecting cosmic ray intensity:
3) CMEs and other Solar Transients

- Both the CME rate and mass reached minimum levels in 2007-2008
- The CME rate has been increasing since mid-2009

Vourlidas et al. (2010) (Robbrecht et al.; St. Cyr, 2009)
Cosmic Rays before the Space Era

Robert A. Millikan launching two balloons in 1938 to measure cosmic rays high in the atmosphere.

Courtesy of the Caltech Archives
Reconstructed Climax Neutron Monitor, 1933-2010

blue - Based on ionization chambers (Neher 1971, Forbush)
Red - Climax neutron monitor
Black – scaled from Newark Neutron Monitor by RM

McCracken and Beer, 2007
THE PALEO-COSMIC RADIATION RECORD

GALACTIC COSMIC RADIATION → SPALLATION OF ATMOSPHERIC N AND O.

$T_{1/2} = 5730$ yr

$14C$ $10Be$ $T_{1/2} = 1.4$ Myr

TREE RINGS

DIFFERENT ATMOSPHERIC EFFECTS

ICE CORE

TIME
Effects on $^{10}$Be Production Rates

By correcting the measured production rate with the latitude and magnetic dipole moment at the time it is possible to derive a value for the "modulation parameter" in the past.

Figures from Masarik and Beer (2009)
The space era has occurred during a period of low cosmic ray activity.

Steinhilber et al. 2010
Consistent $^{10}$Be and $^{14}$C records over the last 9300 years

Beer et al, ICRC 2007

40-year running means
Deriving the Interplanetary Magnetic Field Strength (IMF) from the Modulation Factor ($\phi$) - see Steinhilber et al. 2009, 2010

$$\phi(t, r) = \int_r^{r_b} \left( \frac{v_{SW}(t, r')}{3 \kappa(t, r')} \right) dr',$$

If $\kappa \propto B^{-\alpha}$ Caballero-Lopez et al. (2004)

Then

$$B_{IMF}(t) = B_{IMF,0} \times \left( \frac{\phi(t)}{\phi_0} \frac{v_{SW,0}}{v_{SW}} \right)^{1/\alpha}$$

Test using 1964-2010 OMNI2 IMF data (---) and neutron monitor determination of $\phi$ (---)

Steinhilber et al. 2009
\[ B_{\text{IMF}} \text{ over the last 9300 years} \]

Assuming an average value for \( V_{SW} \) Steinhilber et al (2010) derived \( B_{\text{IMF}} \) for the past 9300 years:

Steinhilber et al. 2010
Relating TSI from the Open Component ($B_R$) of the IMF

Frohlich (2009)
TSI during the Holocene – Steinhilber et al. 2010

Relative to 1365.57 W/m² as measured in 1986
We have been in a Grand Maximum since ~1945. Based on the length of previous Grand Maxima, Abreu et al. (2008) conclude that it is likely to end within ~15 years.

Abreu et al. 2008
In the next few years, Voyager-1 will enter our nearby galactic neighborhood where it may measure local-interstellar cosmic-ray energy spectra.
Comparison of LIS Spectra for Hydrogen

![Graph showing the comparison of LIS spectra for hydrogen with different models and data sets.](image-url)
Summary

- The current solar minimum created “perfect storm” conditions for “super-fluxes” of cosmic rays at 1 AU.
  - weakened $<B>$ and $<\delta B>$
  - reduced CME rate, mass, and kinetic energy
  - the extended solar minimum $\Rightarrow$ time to equilibrate
  - reduced solar wind dynamic pressure
  - (eventually) flattened heliospheric current sheet

- The extended solar minimum provides the opportunity to isolate these contributions

- The $^{10}$Be record shows that higher GCR intensities have been the rule in the past. We may now be returning to a more normal interplanetary radiation environment

- The cosmic ray intensity is inversely correlated with the IMF, which in turn is correlated with TSI. As a result, these cosmogenic nuclei can trace solar activity in the past.

- According to Abreu et al., the current Grand Maximum is likely to end in the next 15 years or so

- In the next few years Voyager may measure the local interstellar spectra. They could reveal the maximum GCR intensity in the past (and the future), and will affect the interpretation of $^{10}$Be in ice cores
T SI - Comparison with other Reconstructions

This work (cycle average)

Krivova et al. (2007)

Wang et al. (2005)

Lean (2000)

Lean et al. (1995)

Maude r Minimum

1600 1700 1800 1900 2000

Year

Steinhilber et al. 2010b
Do Cosmic Rays affect Cloud Cover?

In a series of papers, Svensmark and co-workers have concluded that cosmic rays play a major role in producing clouds.

Sloan and Wolfendale (2008) conclude that <23% (95% confidence level) of the 11-year cycle change in the globally-averaged cloud cover in solar cycle 22 was due to change in the rate of ionization from the solar modulation of cosmic rays.

**Figure 1.** The LCC anomaly as a function of time for various ranges of vertical cut off rigidity (VRCO). The smooth curve shows a fit of the monthly mean of the daily sun spot number (SSN) with an assumed linearly falling systematic change. The SSN is anti-correlated with the CR count rate with a lead time of some months.
Webber & Higbie (2010a) also re-evaluated the He LIS based on a new model and Voyager data.
Statistics of Grand Maxima – Abreu et al. (2009)
For vertically incident particles the minimum rigidity particle that can reach the upper atmosphere of Earth is given approximately by: \( R_c = 14.5 \cos^4 \lambda \) GV, where \( R_c \) is called the geomagnetic cutoff rigidity (in GV) and \( \lambda \) is the geomagnetic latitude. The plot below is based on a more exact calculation.

Selesnick et al. 2007
Cosmic Ray Intensity and Ionization Rate at Various Cutoff Rigidities
(Data from Lebedev Institute Balloon Flights)

Omni-directional Cosmic-Ray Intensity

Ionization Rate

Cutoff Rigidity (GV)

$N(h), \text{cm}^{-2} \text{s}^{-1}$

$q(h), \text{cm}^{-3} \text{s}^{-1}$
Where the measurements fall along the cosmic ray spectrum observed near Earth.

The peak of the intensity spectrum has been relatively well covered.
Solar/Interplanetary parameters affecting cosmic ray intensity:

2) Solar Wind Velocity (Vsw)

- Vsw directly affects the loss rate of cosmic rays due to convection
- The drop in speed in 2008 is not unusual; there is an increase in early 2010 just as the GCR intensity drops
Solar/Interplanetary parameters affecting cosmic ray intensity:

3) Decreased solar-wind dynamic pressure

- This decrease means that the termination shock and heliopause are moving in => easier GCR access to 1 AU
- However, both Voyager and solar modulation models find small radial gradients in the outer heliosphere. This is probably not a major effect at 1 AU

McComas et al., 2008